

HOW TO MAKE A SINGLETON SDB STAR VIA ACCELERATED STELLAR EVOLUTION

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ABSTRACT

Many hot subdwarf B stars (sdBs) are in close binaries, and the favored formation channels for subdwarfs rely on mass transfer in a binary system to strip a core He burning star of its envelope. However, these channels cannot account for sdBs that have been observed in long period binaries nor the narrow mass distribution of isolated (or “singleton”) sdBs. We propose a new formation channel involving the merger of a helium white dwarf and a low mass, hydrogen burning star, which addresses these issues. Hierarchical triples whose inner binaries merge and form sdBs by this process could explain the observed long period subdwarf+main sequence binaries. This process would also naturally explain the observed slow rotational speeds of singleton sdBs. We also briefly discuss the implications of this formation channel for extreme horizontal branch morphology in globular clusters and the UV upturn in elliptical galaxies.

Subject headings: binaries: close — subdwarfs — stars: evolution

1. INTRODUCTION

Hot subdwarf B stars (sdBs) are thought to be core helium burning stars with thin hydrogen envelopes (for a recent review, see Heber 2009). Here, we define sdBs by observable quantities as stars with $5.0 < \log g < 6.6$ and $20000 < T_{\text{eff}} < 45000$ (see Wade et al. 2010). To explain the origin of sdBs, a theory must account for simultaneous mass loss and He ignition near the tip of the red giant branch (RGB). Many formation channels invoke binary mass transfer to account for the loss of the H rich envelope (e.g., Mengel et al. 1976; Han et al. 2002, 2003). This mass loss mechanism is supported by observations that show that 69% of sdBs are found in close binaries (Maxted et al. 2001). However, there are also many ostensibly single sdBs, and Copperwheat et al. (2011) presented a revised estimate for the binary fraction in sdBs of only 51%. The masses of some of these “singleton” sdBs have been estimated with asteroseismology, and are seen to be narrowly distributed around $0.47 M_{\odot}$ (e.g., Charpinet et al. 1997; van Grootel et al. 2010). There are many proposed formation channels for single sdBs, including the merger of two He white dwarfs (WDs) (Webbink 1984; Iben & Tutukov 1984, 1986), enhanced RGB mass loss (D’Cruz et al. 1996), ejection of the H envelope by a sub-stellar companion (Soker 1998), and centrifugally enhanced mass loss triggered by common envelope (CE) mergers (Politano et al. 2008). Recent observations of a sdB with a sub-stellar companion and a rapidly rotating, isolated sdB might be evidence of the latter two channels (see Geier et al. 2011b,a), but otherwise, evidence supporting the latter three channels is meager. Furthermore, the population synthesis models presented by Han et al. (2002) suggest that WD mergers would lead to a wide distribution in the masses of single sdBs, contrary to what is observed. We propose that singleton sdBs can be the result of a binary merger, not of two He WDs as previous studies have presented, but rather the merger of a He WD and a very low mass hydrogen burning star.

2. ACCELERATED STELLAR EVOLUTION

Given enough time, low mass stars can evolve directly to the sdB stage, by way of RGB mass loss and He ignition under degenerate conditions. Such low mass stars naturally lose their entire H envelopes by a Reimers-like wind, and thus form singleton sdBs. To delineate the ZAMS mass range, RGB mass loss rate, and timescales required to form sdBs from single stars, we ran stellar evolution models using the fast Single Star Evolution code (SSE) described in Hurley et al. (2000) and confirmed the results with more detailed models using the one-dimensional stellar evolution code MESA star described in Paxton et al. (2011). The Reimers mass loss rate is given by $\dot{M} = 4 \times 10^{-13} \eta RL/M M_{\odot} \text{yr}^{-1}$, where R , L , and M are the star’s radius, luminosity, and mass, respectively, and η is a tunable parameter (Kudritzki & Reimers 1978). For values of η in the range 0.1 - 0.5, stars with initial masses in the range $M_{\text{ZAMS}} = 0.53 - 0.84 M_{\odot}$ will evolve to the sdB stage, see Figure 1. The resulting sdBs are all concentrated in mass at the usual He ignition mass at the tip of the RGB, $0.47 - 0.51 M_{\odot}$, which would account for the observed narrow mass distribution of singleton sdBs with precise mass determinations. The problem is that the universe is not yet old enough for this to have occurred in the single star context. Given the usual composition, $Y \sim 0.25 - 0.28$, it takes between 25 and 80 Gyr for these single stars to evolve into sdBs. However, if the evolution of the star could be accelerated, singleton sdBs could form in the observed mass range at the present epoch, directly from low mass stars.

2.1. Binary Evolution

Injecting an already formed He core into a low mass star can “create” a $0.53 - 0.84 M_{\odot}$ star that is already at an advanced evolutionary age, so that it can ascend the giant branch and ignite He within a Hubble time. The preformed He core is delivered in the form of a He WD, the remnant of mass transfer in a previous stage of close binary mass exchange. This scenario requires a binary

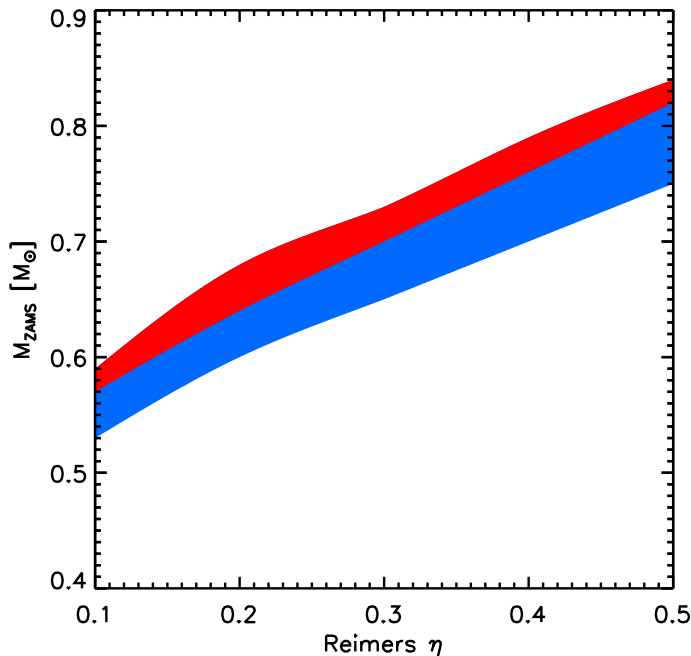


FIG. 1.— ZAMS mass ranges that result in the formation of a sdB for different values of the Reimers mass loss parameter η . For the upper, red region, we have assumed that He ignition occurs at the tip of the RGB. If we allow stars to ignite He when the core has reached 95% of the mass it will have at the tip of the RGB (D’Cruz et al. 1996), the mass range includes the red region and extends to the lower values shown in blue. These models were computed with SSE assuming solar abundances. This band shifts to the right for stars with $Y = 0.6$.

consisting of a primary that is massive enough to have evolved to the RGB in less than a Hubble time and an M dwarf companion.

We illustrate this formation pathway with an example computed using the Binary Star Evolution code (BSE) described in Hurley et al. (2002). Initially, the binary consisted of a $1.5 M_{\odot}$ primary and a $0.25 M_{\odot}$ companion with an orbital period of 75 days. After 2.9 Gyr, the primary began moving up the giant branch and expanded to fill its Roche lobe, resulting in unstable mass transfer. The system went through a CE phase during which the primary’s H envelope was ejected. The system emerged as a $0.33 M_{\odot}$ He WD and a $0.25 M_{\odot}$ companion with an orbital period of 4 hours. The system then underwent a period of tidal readjustment that further reduced the orbital separation and caused the low-mass, hydrogen burning star to fill its Roche lobe. Low mass main sequence stars are deeply convective, so the mass transfer was unstable and the stars coalesced into a $0.57 M_{\odot}$ star with a $0.33 M_{\odot}$ He core. Using MESA star and SSE, we calculated how long it would take a $M_{ZAMS} = 0.6 M_{\odot}$ star to evolve to a similar structure and found times of 79 and 82 Gyr, respectively. However, through accelerated stellar evolution the coalesced binary reaches this evolutionary state in only 5.1 Gyr. While BSE was adequate for modeling the binary evolution, we needed to use SSE and MESA star to investigate the evolution of the merger product.

2.2. Evolution of the Merger Product

After the binary coalesced, BSE continued to evolve the merger product as a single star and, in the illus-

trative case described above, the merger product eventually reached the sdB stage. However, based on the merger product’s core mass, BSE assumed that it was a $M_{ZAMS} = 2.5 M_{\odot}$ star at the base of the RGB and evolved the star accordingly. This assumption is clearly not appropriate to model the evolution of a $0.57 M_{\odot}$ star, so we used SSE and MESA star to find stars with core-envelope structures similar to the merged star from the BSE model. As described above, the stellar evolution models showed that a star with $M_{ZAMS} = 0.6 M_{\odot}$ eventually formed a $0.33 M_{\odot}$ He core surrounded by a $\sim 0.25 M_{\odot}$ H rich envelope. When we continued the evolution of this star, the mass of the He core grew through H shell burning and ignited at the tip of the giant branch while Reimers mass loss removed the remaining H envelope. This additional evolution from the RGB to the sdB stage took 140 Myr. The evolutionary tracks computed by SSE and MESA star are shown in Figure 2. If the merged He WD–M dwarf maintains the distinct core-envelope structure of an RGB star, then the binary evolution scenario described above forms a $0.48 M_{\odot}$ sdB in 5.2 Gyr.

It is not clear whether the merged star will maintain the core-envelope structure of an RGB star. Instead, some mixing might occur that would alter the chemical profile assumed above. To bracket the range of possible outcomes, we explored models in which the He WD mixed completely with the M dwarf and formed a homogeneous, He-rich star. In the mergers considered here, we are mixing $\sim 0.2 M_{\odot}$ of material with standard abundances with $\sim 0.3 M_{\odot}$ H depleted material, resulting in a star with $Y \sim 0.6$. Using MESA star, we have modeled the evolution of these completely mixed stars and found that they too will form sdBs. Figure 3 shows evolutionary tracks in the $(\log T_{eff}, \log g)$ plane for $0.6 M_{\odot}$ and $0.7 M_{\odot}$ mixed stars with $\eta = 0.5$ and 0.7 , respectively, and initial $Y = 0.6$. The less massive star takes 5.8 Gyr to become a sdB and remains in the sdB “box” for 210 Myr, while the more massive star evolves to the sdB stage in only 3.3 Gyr and remains in this stage for 110 Myr. The sdB stars have masses of $0.44 M_{\odot}$ and $0.50 M_{\odot}$, respectively. For comparison, the evolutionary track of the $0.6 M_{\odot}$ mixed star is also shown in Figure 2. These models demonstrate that even if the preformed He core dissolves during the merger, these systems can still evolve into sdBs within a Hubble time.

3. DISCUSSION

This formation channel depends on several assumptions made in modeling binary stellar evolution. The initial configuration of the binary must be such that the primary evolves to the giant branch and triggers an episode of unstable mass transfer that completely removes its envelope before the merger. Furthermore, the total mass of the merged star must be in the range $0.53 - 0.84 M_{\odot}$ for the merged object to evolve into a sdB. We have computed a grid of models with $\eta = 0.3$ to make a preliminary exploration of the parameter space of progenitor systems with primary masses in the range $1 - 3 M_{\odot}$, secondary masses in the range $0.1 - 0.8 M_{\odot}$, periods in the range $1 - 350$ d, and CE ejection efficiencies, α_{CE} , in the range $0.5 - 1.5$. Of the 5×10^4 models in our grid, 6% produce merger products that will evolve into sdBs within a Hubble time. We have assumed

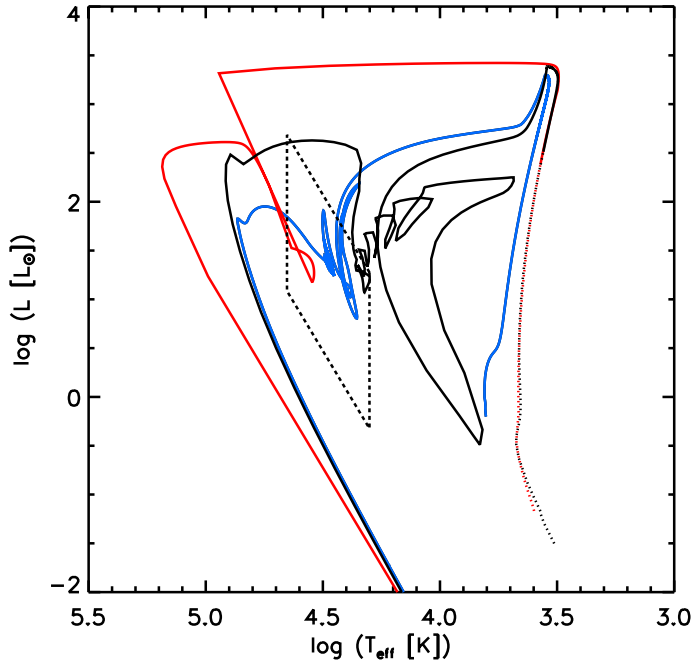


FIG. 2.— $T_{\text{eff}} - L$ diagram showing three single stellar evolution models that result in the formation of a sdB. The initial mass for each model is $0.6 M_{\odot}$. The black and red curves show models with $Y = 0.28$ and were computed with MESA star and SSE, respectively. The dotted portions of these curves are the ~ 80 Gyr of evolution that are “skipped” by merging a He WD with an M dwarf. The excursion to low luminosity after reaching the tip of the RGB seen in the MESA star model occurs on a timescale of 2×10^4 yr. The blue curve shows a model with $Y = 0.6$ and was computed with MESA star. The dashed lines show the “sdB box” for $0.48 M_{\odot}$ sdBs.

that the core-envelope structure is retained and used the results of Figure 1. The primary masses in these systems range from $1.2 - 3 M_{\odot}$, the secondary masses range from $0.1 - 0.6 M_{\odot}$, and the initial periods range from $10 - 350$ d. In many cases, the CE phase was sufficient to remove the primary’s envelope and drive the system to merger so that the tidal readjustment phase described above was not required. For each value of α_{CE} roughly the same number of proto-sdBs were formed, except for $\alpha_{CE} = 0.5$ which produced 30% fewer sdB progenitors. In this case many binaries merge before the primary’s envelope is removed, producing an RGB star that is too massive to evolve directly to the sdB stage. A full exploration of the parameter space and formation rate requires further work, but we note that our preliminary investigation suggests that a diverse population of initial binaries will evolve into singleton sdBs and that this result holds for a wide range of values for α_{CE} and η . Furthermore, since both members of the initial binary are of relatively low mass, their formation is favored by the observed Initial Mass Function.

The time required to form a singleton sdB with this channel varies widely. In one extreme, a binary consisting of stars with masses of $3 M_{\odot}$ and $0.35 M_{\odot}$ with a 90 d period merged after only 380 Myr, implying that if the merger product maintains its core-envelope structure, this system could form an sdB within ~ 0.5 Gyr of its birth. On the other hand, some systems take more than a Hubble time to coalesce and, if the merged star mixes it could take an additional 6 Gyr to evolve to the sdB stage. From our grid of models, the mean amount of

time for a system to merge into a proto-sdB was 5.5 Gyr. More work is needed to study the chemical stratification of the merger product, but the time it takes the merged star to become an sdB is bracketed by the 140 Myr and 3-5 Gyr time scales for the non-mixed and completely mixed cases, respectively.

3.1. Long Period sdB+Main Sequence Binaries

This channel may also explain a conundrum among the presently observed sdB + G or K dwarf binaries. (We will use “MS” as shorthand notation for G and K dwarfs.) Han et al. (2003) predicted that all such systems form as the result of a CE phase and should have periods $\lesssim 20$ d. These authors also predict long period ($P \gtrsim 40$ d), post-Roche lobe overflow sdB + G or K binaries, but in these systems the companions are subgiants or giants (i.e., more massive stars at a later evolutionary state). The short period, sdB+MS binaries should be easy to find because their large velocity variations can easily be discerned within a single observing run, but none have been reported. The observational evidence suggests that the presence of a G or K dwarf companion indicates a wide ($P > 100$ d) binary (see, e.g., Copperwheat et al. 2011, and references therein), despite the suggestion of Heber et al. (2002) that radial velocity observations should reveal such sdB+MS systems to be close. Our own experiments with BSE, including various modifications to the mass loss, angular momentum loss, and stable mass transfer criterion (some of which mimic the results of Han et al. 2003), fail to produce long period sdB+MS binaries. But if these sdB+MS binaries are instead viewed as the binary remnants of original hierarchical triple systems, in which the inner binary has evolved to become a singleton sdB as outlined above, then the remaining outer binary (presently seen as sdB+MS) was never “close” (i.e., tidally interacting) and is thus irrelevant to the production of the sdB.

For stability of the hierarchical triple, the ratio of the semi-major axis of the outer binary to that of the inner, sdB forming binary must be greater than $\sim 20 \log(1 + m_3/m_B)$, where m_3 is the mass of the outer star, m_B is the mass of the inner binary, and we have assumed circular orbits (Harrington 1975). Furthermore, as mass is lost by the inner binary to form the sdB, the orbit of the outer binary will expand adiabatically to $a_f = a_i(M_i/M_f)$, where a is the semi-major axis and M is the total mass of the system and the subscripts i and f correspond the value before and after mass loss, respectively (Eggleton et al. 1989; Debes & Sigurdsson 2002). If we apply these constraints to the illustrative case described above and assume that this binary is orbited by a $0.8 M_{\odot}$ K dwarf, the *minimum* orbital period of the resulting sdB + K dwarf binary is 1360 d. When we consider the entire grid of models discussed above, the shortest possible period for a sdB + $0.8 M_{\odot}$ K dwarf binary is 185 d. Furthermore, we note that the outer star might promote the merger of the inner binary via the Kozai mechanism. This triple-star channel, involving the new H-merger channel described above, can produce long period sdB+MS binaries, so previous studies of the sdB+MS binary population that do not include this channel are incomplete.

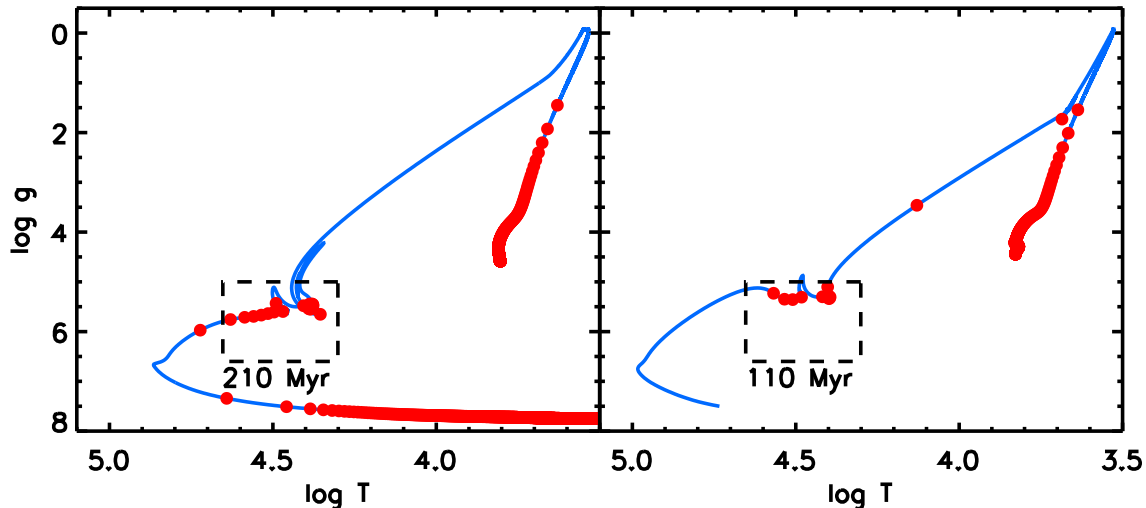


FIG. 3.— Surface gravity vs. effective temperature for $Y = 0.6$ stars. The left and right panels show the evolution of the quantities for stars of initial mass $0.6 M_{\odot}$ and $0.7 M_{\odot}$, respectively. The dots are evenly spaced in time, each interval corresponding to 10 Myr of evolution. Dashed lines show the “sdB box” and the total duration of the sdB phase for each star is noted on the plot.

3.2. Rotation of Single sdBs

Gourgoulatos & Jeffery (2006) studied the merger of two He WDs assuming complete conservation of momentum and found that the rotational velocity of the merger product could be $\gtrsim 10^3 \text{ km s}^{-1}$. While there is undoubtedly some angular momentum lost during the merger, it is difficult to explain why nearly all single sdBs observed have projected rotational velocities of $< 10 \text{ km s}^{-1}$ (Geier et al. 2009). An advantage of the new H-merger channel described above is that the merger product will lose between $\sim 0.1 - 0.3 M_{\odot}$ of material while it is on the giant branch. Angular momentum carried away by this material can spin down the star, resulting in a slowly rotating sdB.

3.3. Other Implications

Contributions from the He WD + M dwarf formation channel for sdBs presented here might also play a role in determining the binary fraction of extreme horizontal branch (EHB) stars in globular clusters, and in the UV-upturn in elliptical galaxies. The short-period binary fraction among EHB stars in globular clusters is much lower than that of field sdBs, and this has been attributed to the fact that the dominant formation channel for EHBs in old stellar populations is He WD mergers that result in a singleton sdB (Moni Bidin et al. 2008; Han 2008; Moni Bidin et al. 2011). The formation channel presented here also produces singletons, and in some cases, especially if the merger product is mixed as considered above, the process can take $\gtrsim 12 \text{ Gyr}$ to produce a sdB. These mixed stars would exhibit the super-solar helium abundance invoked in some EHB models (e.g., Sweigart & Mengel 1979; Dalessandro et al. 2011), although star-by-star rather than as a population. Again, more work is needed to determine whether this channel contributes to the EHB population significantly at late times.

Finally, we note that sdBs produced by this merger channel could also contribute to the UV-upturn observed in elliptical galaxies. The evolved stellar populations

thought to inhabit elliptical galaxies would not produce the UV-excess seen in their spectral energy distributions, and Han et al. (2007) proposed that emission from the sdBs formed through binary evolution might be the source of this radiation. The formation channel presented here offers an additional population of sdBs that supplies UV photons, perhaps on a different timescale. Determining the contribution of singleton sdBs formed by He WD + M dwarf mergers to either the globular cluster or elliptical galaxy populations is further complicated by metallicity effects.

4. CONCLUSIONS

We have shown that merging a He WD with an M dwarf can produce a low mass star of advanced evolutionary age or a helium rich star, either of which can evolve to become a sdB within a Hubble time. This model can explain the narrow mass range in singleton sdBs and the existence of long period sdB+MS binaries, if these systems were initially triples. The sdBs produced by this formation channel might also contribute to the low binary fraction among EHB stars in globular clusters and the UV-excess in elliptical galaxies. Many aspects of this channel remain to be explored, including the formation rate, the effect of metallicity variations, and the exact chemical profile of the merger product. We offer it as a supplementary and possibly dominant channel for formation of singleton sdBs.

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